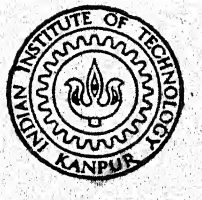
MEASUREMENT OF THE AGE OF PLUTONIUM-BERYLLIUM NEUTRONS TO INDIUM-RESONANCE, IN AN ALUMINIUM-WATER SLAB LATTICE

KALIMULLAH



DEPARTMENT OF MECHANICAL ENGINEERING
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MEASUREMENT OF THE AGE OF PLUTONIUM - BERYLLIUM NEUTRONS TO INDIUM - RESONANCE IN AN ALUMINIUM - WATER SLAB LATTICE

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CERTIFICATE

This is to certify that the present work has been carried out under my supervision and that the work has not been submitted elsewhere for a degree.

G. SRIKANTIAH
Professor & Head
Department of Mechanical Engg.,
Indian Institute of Technology,
KANPUR (INDIA)

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CONTENTS

LIST OF SYMBOLS

E	- Neutron energy
r	- Radial distance from neutron source
$q(r,E)$	- Neutron slowing-down density past the energy E at a distance r
S	- Strength of the neutron source
$S(E)$	- Energy-spectrum of the neutron source
τ	- Neutron age
$q(r,E \rightarrow E_f)$	- Slowing-down kernel
$A_s(r)$	- Saturation activity of the foil at a distance r from the source
V	- Volume of an activation foil
$\phi(r,E)$	- Energy-dependent neutron flux at a distance r from the source
$\Sigma_a(E)$	- Energy-dependent macroscopic absorption cross-section of the foil
$\Sigma_{sm}(E)$	- Energy-dependent macroscopic scattering cross-section of the medium in which the foil is immersed
ξ	- Average logarithmic energy decrement in the medium in which the foil is immersed
t	- Time
B	- Background counts
C	- Counts observed with a foil
η	- Counting efficiency of the counter
t_c	- Counting time for each side of a foil

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ABSTRACT

This experiment aims at studying the anisotropy of the slowing-down distribution arising from a Pu-Be neutron source in an Al-H_2O slab lattice composed of 3.175 mms thick Al-plates and 10.00 mms thick H_2O-layer in-between. A measure of the maximum anisotropy of the slowing-down distribution is expected to be given by the difference between the neutron ages in the two extreme directions, one parallel to the Al-plates, and the other perpendicular to the Al-plates. Since these two directions are the extremes of all possible directions, the neutron age in any other direction lies between these two age values.

In order to do this, the neutron ages from the Pu-Be spectrum to the In-resonance, both in the parallel and perpendicular directions, are measured by the foil activation technique. The flux perturbation due to the introductio of a different material in the lattice is minimised by using a minimum of the structural material used to hold the source and to suspend the foils. Approxim corrections are applied to the measured activities to correct them for the high energy activation and the finite sizes of the source and the foil. Finally, the statistical errors in the two age values due to statistical errors in the measured activities are calculated.

The neutron ages in the parallel and perpendicular directions are found to be 79.33 ± 0.444 cm^2 and 71.85 ± 0.470 cm^2 respectively. That the age in the parallel direction is greater than the age in the perpendicular direction is explained qualitatively on the basis of the comparative values of the age-average scattering cross-sections (a concept developed in this work) of Al and H_2O.

CHAPTER I

INTRODUCTION

1.1 The Problem and its Purpose :

Neutron age is an important parameter whose square-root gives a measure of the slowing-down length from a higher energy to a lower one in a moderating medium. Actually, the age of neutrons in a moderating medium is defined as one-sixth the average square distance a neutron travels during slowing down from a higher energy to a lower one. The importance of age basically comes out of the fact that the fast neutron nonleakage probability for a finite reactor depends upon this parameter. Other parameters remaining constant, the fast nonleakage probability decreases as the neutron age increases.

A series of age measurements in different moderating media such as light water, Aluminium-water slab lattice, Paraffin, etc. are proposed to be performed in the Nuclear Engineering Laboratory. Recently the age of Plutonium-Beryllium source neutrons to Indium-resonance in light water has been measured by foil activation technique[13]. The present experiment aims at studying the anisotropy of slowing-down distribution, parallel and perpendicular to aluminium plates, in an Aluminium-water slab lattice arising from a point neutron source. The neutron ages from Plutonium-Beryllium source spectrum to Indium-resonance, are measured by foil activation technique, both in the parallel and perpendicular directions. The difference between the two age values is expected to give a measure of the anisotropy of the slowing-down distributions in the two directions.

Since these two directions are the extremes of all possible directions, the neutron age in any other direction lies between these two age values, and the difference between these two values is a measure of the maximum anisotropy in the system.

The purpose of the problem lies in the fact that in certain water-moderated reactors, fuel elements in the form of plates containing comparatively small fractions of the fissile isotope in a matrix mainly composed of Aluminium, have been used. Since the fissile isotope forms a small fraction of the plate, is costly and difficult to obtain, and gives rise to many technical difficulties, the measured values are taken as reliable approximations to the actual values in such lattices.

1.2 Review of Literature :

Both experimental and theoretical values of neutron age from fission and other sources to Indium-resonance in pure water and in Aluminium-water mixtures are available. Table (1) is a list of almost all neutron age determinations in pure water and in Aluminium-water mixtures published from 1961 to 1969. In general, the experimental values are higher than the theoretical values. This disagreement has been well understood in case of the fission neutron age in water. Harry Alter[8] has made Monte Carlo calculations for the age of fission neutrons in water including inelastic scattering and anisotropic elastic scattering effects, using different fission spectra and different sets of Oxygen cross-section and angular distribution data. The calculated slowing-down ages after applying suitable corrections compare well with the experimental flux ages.

J.W. Cooper[2] has made Monte Carlo calculations for the age of D-D neutrons in water using different duct sizes for the deuteron beam and two different deuteron energies. The computed values compare well with experimental results.

Spencer and Williamson[10] have measured fission neutron age in an Aluminium-water mixture of $Al/H_2O = 2/3$ using two thicknesses for Al-plates, 0.1 inch and 0.5 inch, and observed no effect of heterogeneity.

P.F. Palmedo[11] has measured fission neutron age in Aluminium-water plate lattices both in the parallel and perpendicular directions. Palmedo[12] has also made Monte Carlo calculations for the same in many lattices. In general the experimental values are higher than the calculated values. At a given Al/H_2O ratio the age perpendicular to plates increases relatively slowly with plate thickness. The age perpendicular to plates requires a relatively small correction in order to reduce it to the corresponding homogeneous value whereas the age parallel to plates requires a correction of - 5.0%. The anisotropy also goes on increasing with plate thickness.

The anisotropy of the slowing-down distribution of Pu-Be or any other neutron source has not been studied in $Al-H_2O$ or any other plate lattice.

1.3 Errors and Difficulties in the Experiment :

In this work the foil activation technique is used, the analysis of which is given in the next chapter. The difficulties and

sources of error associated with the experiment are due to finite sizes of the neutron source and the activation foil. In practice the foil cannot be just an ideal point-foil. Since the age value is more sensitive to the activities measured at larger distances from the source where the activities are comparatively small and hence statistical errors large, the neutron source should be sufficiently strong for the statistical error in the final age value to be smaller than a certain maximum. The counts observed from foils at larger distances from the neutron source are required to be sufficiently large. In order to correct for finite sizes of source and foil, approximate corrections are required. Another difficulty is that some structural material other than the moderating medium are required and this difficulty can be overcome by using a minimum of such material, and by choosing the structural material which has slowing-down properties similar to those of the moderating medium. Finally, a suitably finite moderating medium has to be used as a reliable representation of the theoretical infinite medium.

TABLE 1

NEUTRON AGE TO INDIUM - RESONANCE

Published from 1961 to 1969

Year	Investigator and method	Medium	Source	Age in cm^2
1961	Doerner et al[1] PA	Water	Fission	27.86 ± 0.10
1961	J.W. Cooper[2] MC	Water	D-D	Table in Reference
1961	Amster and Gast[3] PA	Water	Fission	25.2 ± 0.1
			Ra - Be	13.33 ± 0.05
1961	De Juren et al[4] PA	Water	1.4 MeV D-D	54.4 ± 1.4
1961	Amster and Gast[5] PA and MC	Water	D-D	63.0 ± 0.5
				64.5 ± 0.5
1962	Joanou et al[6] MM	Water	Fission	26.4
			Po - Be	58.5 ± 1.5
			Na^{24}-Be	14.0
			N^{17}	14.5
			Ra-Be	56.7
1964	R.K. Paschall[7] PA	Water	Fission	26.8 ± 0.32
1965	Harry Alter[8] MC	Water	Fission	Tables in Reference

TABLE 1 CONTD.

Year	Investigator and method	Medium	Source		Age in cm^2	
1966	R.K. Paschall[9] FA	Al-H_2O	Fission	Al/H_2O	Age	
				0.25	33.9 ± 0.6	
				0.50	43.2 ± 0.8	
				1.0	59.6 ± 0.9	
1967	Spencer and Williamson[10] FA	Al-H_2O	Fission	1/4	32.28 ± 0.5	
				1/2	39.96 ± 0.5	
				2/3	44.88 ± 0.59	
				2/3 (lumped)	44.50 ± 0.49	
1968	P.F. Palmedo[11] FA	Al-H_2O	Fission	Al/H_2O	Parallel	Perp.
				1/1	65.4 ± 0.8	60.8 ± 0.8
				2/1	100.3 ± 1.5	92.5 ± 1.3
1968	P.F. Palmedo[12] MC	Al-H_2O	Fission	Tables in Reference		

FA = Foil Activation Method

MC = Monte Carlo Method

MM = Moments Method

CHAPTER II

AGE MEASUREMENT TECHNIQUE

2.1 Definition of Neutron Age :

The neutron age from an energy E_o, well above the thermal region, to a lower energy E in the slowing-down region, in a non-absorbing moderating medium is defined as one-sixth of the average of the square of the crow-flight distance that a neutron emitted by a point isotropic steady monoenergetic source of energy E_o travels in an infinite bulk of the moderating medium from the source to the point where it slows down past the energy E.

Let r = the radial or crow-flight distance from the source to a point in the moderating medium,

p(r)dr = the differential probability that a neutron emitted by the source slows down past the energy E between the radial distances r and r + dr,

q(r,E) = the slowing-down density at any radial distance r from the source past the energy E, that is, the number of neutrons per unit volume at any radial distance r from the source slowing down past the energy E per unit time,

and S = the strength of the source, that is, the number of neutrons emitted per unit time by the source.

Then the number of neutrons slowing down per unit time past the energy E in the differential spherical shell of in-radius r and ex-radius r+dr

= the volume of the shell X the slowing-down density at

distance r from the source past the energy E

$$= 4\pi r^2 q(r, E)\, dr \qquad (1)$$

The differential probability p(r) dr that a neutron emitted by the source slows down past the energy E between the radial distances r and r + dr

$$= \frac{\text{the number of neutrons slowing down per unit time past the energy E in the differential spherical shell of in-radius r and ex-radius r + dr}}{\text{the total number of neutrons emitted per unit time}}$$

and hence p(r)dr can be expressed in terms of slowing-down density as

$$p(r)dr = \frac{4\pi r^2 q(r,E)dr}{S} \qquad (2)$$

Let $\tau(E_0 \longrightarrow E)$ = the neutron age from an energy E_0 to a lower energy E,

and then it follows from the definition of the neutron age given above that

$$\tau(E_0 \longrightarrow E) = 1/6 \int_0^{\infty} r^2 p(r)dr \qquad (3)$$

Using the equation (2) in order to express the neutron age in terms of slowing-down density, the equation (3) can be written as

$$\tau(E_0 \longrightarrow E) = \frac{4\pi}{6S} \int_0^{\infty} r^4 q(r,E)dr \qquad (4)$$

Since the medium is infinite, no neutron emitted by the source can leak out of the moderating medium and since the medium is non-absorbing, the total number of neutrons slowing down per unit time past the energy E throughout the moderating medium, at steady state, must equal the total number of neutrons emitted per unit time by the source, and hence the strength S of the source can be expressed in terms of the slowing-down density as

S = the volume integral of slowing-down density past the energy E over the entire space

or, $$S = \int_0^{\infty} q(r,E)\, 4\pi\, r^2 dr \qquad (5)$$

Using the equation (5) in order to eliminate the source strength S from the expression for the neutron age, the equation (4) can be written as

$$\tau(E_o \longrightarrow E) = 1/6 \; \frac{\int_0^{\infty} r^4 q(r,E) dr}{\int_0^{\infty} r^2 q(r,E) dr} \qquad (6)$$

The equation (6) defines the neutron age from a monoenergetic source of energy E_o to a lower energy E in terms of the slowing-down density past the energy E and forms the basis of other expressions for neutron age which are derived below and are basic to the age measurement technique.

2.2 Neutron Age from an Energy-distributed Source :

Since Plutonium-Beryllium neutron source emits neutrons of all energies with a continuous energy-spectrum, in this article the meaning of the neutron age measured from the source spectrum to a final energy E_f in the slowing-down region is developed. In this case, the measured value of the neutron age depends upon the energy-spectrum of the source.

Let $S(E)dE$ = the differential number of neutrons emitted per unit time by the source in the energy-interval dE between the energies E and $E+dE$,

$q(r,E \rightarrow E_f)$ = the slowing-down density, that is, the number of neutrons slowing down per unit volume per unit time past the energy E_f arising from a unit point isotropic steady monoenergetic neutron source of energy E put in an infinite non-absorbing moderating medium, at a radial distance r from the source,

and $q(r,E_f)$ = the total slowing-down density, that is, the total number of neutrons slowing down per unit volume per unit time past the energy E_f at a radial distance r arising from neutrons of all energies above E_f emitted by the energy-distributed source.

Then the total slowing-down density $q(r,E_f)$ can be expressed in terms of the slowing-down kernel $q(r,E \rightarrow E_f)$ as

$$q(r,E_f) = \int_{E_f}^{\infty} S(E)q(r,E \rightarrow E_f)dE \qquad (7)$$

The average neutron age from the source-spectrum to the energy E_f can be found by inserting $q(r,E_f)$ from the equation (7) into the equation (6), and thus the average neutron age to the energy E_f is expressed as

$$\tau(E_f) = 1/6 \frac{\int_0^{00} \int_{E_f}^{00} r^4 S(E) q(r,E \rightarrow E_f) dE dr}{\int_0^{00} \int_{E_f}^{00} r^2 S(E) q(r,E \rightarrow E_f) dE dr} \qquad (8)$$

Since the moderating medium is infinite and non-absorbing, and the slowing-down kernel $q(r,E \rightarrow E_f)$ is the slowing-down density arising from a unit point isotropic steady monoenergetic neutron source, the volume integral of $q(r,E \rightarrow E_f)$ over entire space must be equal to unity due to reasons given in article 2.1 and thus

$$\int_0^{00} 4\pi r^2 q(r,E \rightarrow E_f) dr = 1 \qquad (9)$$

Using the equation (6) the neutron age from an energy E to the energy E_f can be expressed in terms of the slowing-down kernel $q(r,E \rightarrow E_f)$ as

$$\tau(E \rightarrow E_f) = 1/6 \frac{\int_0^{00} r^4 q(r,E \rightarrow E_f) dr}{\int_0^{00} r^2 q(r,E \rightarrow E_f) dr} \qquad (10)$$

Using the equation (9) the denominator of the expression for the neutron age from an energy E to the energy E_f can be simplified and the equation (10) can be written as

$$\tau(E \longrightarrow E_f) = \frac{4\pi}{6} \int_0^{\infty} r^4 q(r, E \longrightarrow E_f) dr \qquad (11)$$

Now using the equation (9) the denominator of the equation (8) can be simplified and the equation (8) can be written as

$$\tau(E_f) = \frac{4\pi}{6} \frac{\int_0^{\infty} \int_{E_f}^{\infty} r^4 S(E) q(r, E \longrightarrow E_f) dE dr}{\int_{E_f}^{\infty} S(E) dE} \qquad (12)$$

Using the equation (11) the numerator of the equation (12) can be expressed in terms of $\tau(E \longrightarrow E_f)$, the neutron age from an energy E to the energy E_f, and the equation (12) can be written as

$$\tau(E_f) = \frac{\int_{E_f}^{\infty} S(E)\ \tau(E \longrightarrow E_f) dE}{\int_{E_f}^{\infty} S(E) dE} \qquad (13)$$

The equation (13) relates the average neutron age from an energy-distributed source to the neutron ages from monoenergetic sources, and states that the experimentally measured neutron age from an energy-spectrum to the energy E_f is the spectrum-weighted average of the neutron ages from monoenergetic sources to the energy E_f over that part of the energy-spectrum which is above E_f.

2.3 The Foil Activation Technique :

In an experiment on neutron age measurement, the basic quantity to be measured is the neutron slowing-down density at certain points in an infinite (as far as practicable) non-absorbing bulk of the moderating medium, with a point (as far as practicable) isotropic steady neutron source put at a central location inside the system. In the foil activation technique, a foil of a suitable isotope which has a very high and narrow neutron absorption resonance at the energy to which the neutron age is to be measured, is kept at a certain point where the neutron slowing-down density is to be measured, for a period of time large enough for the foil to become almost fully saturated.

Since at the saturation the activity of the foil, that is, the rate of decay of the product nuclei, must be balanced by the rate at which they are produced by neutron irradiation, the saturation activity of the foil is related to the energy-dependent neutron flux as

$$A_s(r) = V \int_0^{\infty} \phi(r,E) \, \Sigma_a(E) dE, \qquad (14)$$

where V = the volume of the activation foil,

$\phi(r,E)$ = the energy-dependent neutron flux, that is, the total track-length of all neutrons in a unit volume at a radial distance r from the source per unit time per unit energy interval taken at an energy E,

and $\Sigma_a(E)$ = the energy-dependent macroscopic absorption cross-section of the isotope of which the activation foil is made.

In order to be exact the integral on the right side of the equation (14) has to be evaluated over the entire energy-spectrum, that is, from zero energy to infinite energy. But the approximate relation which forms the basis of the foil activation technique is readily obtained from the equation (14) in the light of the following three facts :-

(1) The isotope of which the activation foil is made has a very high neutron absorption resonance at the energy to which the neutron age is to be measured and hence almost all the activity of the foil is due to the absorption of resonance neutrons.

(2) The activity due to the absorption of thermal neutrons (for which the absorption cross-section of the isotope of which the activation foil is made is large enough to introduce a considerable error) is eliminated by putting the activation foils in covers made of Cadmium which has very high neutron absorption cross-sections in the thermal region and absorbs practically all the thermal neutrons.

(3) The neutron absorption cross-section of the isotope of which the activation foil is made, in the high energy region is comparatively small and an approximate correction for eliminating the activity induced by neutrons of high energy is applied to the measured activity.

In view of these facts it is a very good approximation to assume that practically all the activity of the foil is induced by

the neutrons of resonance energy and the equation (14) can be approximated as

$$A_s(r) = V \int_{res} \phi(r,E) \Sigma_a(E) dE \qquad (15)$$

The integration on the right side of the equation (15) is assumed to be carried out only over the resonance region. Since the resonance of the isotope of which the activation foil is made, is very narrow, it is a reasonable approximation that the energy-dependent neutron flux $\phi(r,E)$ remains practically constant over the range of integration and hence the equation (15) can be approximated as

$$A_s(r) = V \phi(r,E_{res}) \int_{res} \Sigma_a(E) dE, \qquad (16)$$

where E_{res} = the resonance energy of the isotope of which the activation foil is made.

The integral on the right side of the equation (16) is a constant depending only upon the isotope of which the activation foil is made. The foils used in an activation experiment are all practically identical in shape, size and composition and the volume of an activation foil V is a constant of the experiment and hence the equation (16) states that

$$A_s(r) \propto \phi(r,E_{res}) \qquad (17)$$

Now the Fermi Age Theory gives the following relation between

the neutron slowing-down density and the energy-dependent neutron flux.

$$\phi(r,E) = \frac{q(r,E)}{E\,\xi\,\Sigma_{sm}(E)} \qquad (18)$$

where ξ = the average logarithmic energy decrement of a neutron per collision with the nuclei of the moderating medium surrounding the activation foil,

and $\Sigma_{sm}(E)$ = the energy-dependent macroscopic scattering cross-section of the moderating medium surrounding the activation foil.

Putting in the value of $\phi(r,E)$ in terms of the slowing-down density $q(r,E)$ from the equation (18) into the equation (15), the saturation activity can be expressed in terms of the slowing-down density as

$$A_s(r) = V \int_{res} \frac{q(r,E)}{E\,\xi\,\Sigma_{sm}(E)}\,\Sigma_a(E)\,dE \qquad (19)$$

Since the resonance region is very narrow compared to the slowing-down region, it is a reasonable approximation that the slowing-down density $q(r,E)$, the average logarithmic energy decrement per collision ξ, and the energy-dependent macroscopic scattering cross-section of the moderating medium $\Sigma_{sm}(E)$ remain constant over the range of integration, and hence the equation (19) can be approximated as

$$A_s(r) = \frac{V\,q(r,E_{res})}{\xi\,\Sigma_{sm}(E_{res})} \int_{res} \frac{\Sigma_a(E)}{E}\,dE \qquad (20)$$

The integral on the right side of the equation (20) is a constant depending upon the isotope of which the activation foil is made. Since the foils used in an activation experiment are all practically identical in shape, size and composition, the volume of the activation foil V is a constant of the experiment. The average logarithmic energy decrement per collision ξ, and the resonance macroscopic scattering cross-section $\Sigma_{sm}(E_{res})$ of the moderating medium surrounding the foil are constant throughout the experiment since all the activation foils are immersed in the same moderating medium, and hence the equation (20) states that

$$A_s(r) \propto q(r,E_{res}) \tag{21}$$

The equations (17) and (21) can be combined together to give

$$\phi(r,E_{res}) \propto A_s(r) \propto q(r,E_{res}) \tag{22}$$

Since, in general, at any point in a moderating medium the neutron flux is not isotropic and also the foils used in an activation experiment are many many atoms thick, both sides of an activation foil are not activated equally. Each side is activated almost by the flux of only those neutrons which have a velocity component directed into the foil from that side. The sum of these two side-fluxes at any point, one constituted by only those neutrons which have a velocity component directed into the activation foil from one side and the other constituted by only those neutrons which have a velocity component directed into the foil from the other side of the foil, is the total neutron flux at that point. Thus the saturation activities of both the sides of an activation foil, in general, are not equal and they are each proportional

to their respective side-fluxes. The sum of the saturation activities of both the sides of an activation foil gives a number proportional to the total neutron flux or the slowing-down density at the location of the foil. Using the subscripts 1 and 2 to refer to the two sides of an activation foil, the equation (22) can be modified to take the above fact into account as

$$\phi(r,E_{res}) \propto A_{s1}(r)+A_{s2}(r) \propto q(r,E_{res}) \tag{23}$$

The equation (23) states that the total saturation activity of an activation foil is directly proportional to the neutron flux or the slowing-down density at the location of the foil and is basic to the foil activation technique.

Using the equation (23) in order to express the neutron age in terms of the total saturation activity $A_s(r)$, the equation (6) can be written as

$$\tau = 1/6 \frac{\int_0^{\infty} r^4 A_s(r)dr}{\int_0^{\infty} r^2 A_s(r)dr} \tag{24}$$

where $A_s(r)$ = the total saturation activity of the activation foil kept at a radial distance r from the neutron source.

or, $A_s(r) = A_{s1}(r)+A_{s2}(r)$ (25)

The equation (24) expresses the neutron age in terms of the total saturation activity and is used in the calculation of the neutron age in a foil activation experiment.

2.4 Activation Analysis :

In a foil activation experiment for neutron age measurement, the basic quantity measured is the total saturation activity of a foil kept at a certain point in the moderating medium, for a period of time large enough for the foil to become almost fully saturated. The saturation activity of each side of an activation foil is calculated from the total number of counts of the particles emitted from that side in a certain period of time during the radioactive decay of the product nuclei formed due to neutron irradiation. In this article an expression is developed for the saturation activity of a certain side of an activation foil kept at a certain point in the moderating medium in terms of the total number of counts obtained from a counter in a certain interval of time.

Analysis During Irradiation

Let $N(t)$ = the number of product nuclei at any time t after the foil was put into the moderating medium,

and λ = the decay constant of the product isotope.

The rate of increase of the number of the product nuclei

= the rate of their production due to neutron irradiation

- the rate of their radioactive decay.

The rate of production due to neutron irradiation is equal to the saturation activity, that is, the rate of radioactive decay of the product nuclei at saturation, because at saturation there is set up an equilibrium between the rate of radioactive decay and the rate of

production due to neutron irradiation of the product nuclei, and hence the kinetics of the number of the product nuclei during irradiation is governed by the equation

$$\frac{dN}{dt} = A_s - \lambda N \tag{26}$$

The initial condition to the equation (26) is obtained from the fact that the number of the product nuclei at the instant at which the foil is put into the moderating medium is zero and thus

$$N(0) = 0 \tag{27}$$

The system of equations (26) and (27) yields the solution

$$\lambda N = A_s(1-e^{-\lambda t}) \tag{28}$$

The left side of the equation (28) is the activity at any time t after the foil is put into the moderating medium. The activity builds up exponentially and tends to reach the value A_s asymptotically. In 10 half-lives of the product isotope, the activity attains more than 99.9% of the value of the saturation activity and the foil is supposed to have become almost fully saturated.

Analysis After Irradiation

Let $N(t)$ = the number of product nuclei at any time t after the foil is taken out of the moderating medium,

and N_o = the initial number of the product nuclei at saturation.

After the foil is taken out, the product isotope undergoes exponential radioactive decay and the number of the product nuclei at any time t is given by the equation

$$N = N_0 e^{-\lambda t} \tag{29}$$

The number of the product nuclei that undergo radioactive decay in the interval of time between the instants t_i and t_f

= the number of the product nuclei at time t_i

- the number of the product nuclei at time t_f

$$= N_0 (e^{-\lambda t_i} - e^{-\lambda t_f}) \tag{30}$$

Let η = the counting efficiency of the counter, that is, the number of particles counted, on the average, per particle emitted by that side of the foil which is counted,

C = the total number of counts obtained in the interval of time between the instants t_i and t_f,

and B = the background counts in an equal interval of time.

Then the equation (30) can be written as

$$C - B = \eta N_0 (e^{-\lambda t_i} - e^{-\lambda t_f}) \tag{31}$$

The saturation activity of the side of the foil which is counted, can be expressed in terms of the total counts C and the background counts B,

using the equation (31) as

$$A_s = \lambda N_o = \frac{\lambda (C - B)}{\eta (e^{-\lambda t_i} - e^{-\lambda t_f})} \qquad (32)$$

Let t_c = the counting time (the same for each side),

and t_1, t_2 = the instants at which the counting of the first and the second sides respectively, are started.

Using the subscripts 1 and 2 to refer to the two sides of an activation foil, the saturation activities of the first and the second sides of the foil can then be written as

$$A_{s1} = \frac{\lambda (C_1 - B_1)}{\eta (e^{-\lambda t_1} - e^{-\lambda (t_1 + t_c)})} \qquad (33)$$

and

$$A_{s2} = \frac{\lambda (C_2 - B_2)}{\eta (e^{-\lambda t_2} - e^{-\lambda (t_2 + t_c)})} \qquad (34)$$

Combining the equations (25), (33) and (34), the total saturation activity can be written as

$$A_s = \frac{\lambda}{\eta} \left\{ \frac{(C_1 - B_1)}{e^{-\lambda t_1} - e^{-\lambda (t_1 + t_c)}} + \frac{(C_2 - B_2)}{e^{-\lambda t_2} - e^{-\lambda (t_2 + t_c)}} \right\} \qquad (35)$$

Since the counting efficiency η is maintained constant throughout an activation experiment for neutron age measurement, and the decay constant λ is a constant depending upon the isotope of which the

activation foil is made, the equation (35) can be simplified to

$$A_s \propto \frac{(C_1 - B_1)}{e^{-\lambda t_1} - e^{-\lambda (t_1 + t_c)}} + \frac{(C_2 - B_2)}{e^{-\lambda t_2} - e^{-\lambda (t_2 + t_c)}} \qquad (36)$$

The equation (36) gives a number proportional to the total saturation activity of the foil in terms of the directly observable quantities which are measured in a foil activation experiment for neutron age measurement.

2.5 Neutron-Induced Activities of Indium :

In order to measure the age of Plutonium-Beryllium neutrons to the Indium resonance energy, activation foils made of natural Indium containing 95.77% of Indium-115 and 4.23% of Indium-113 are used in the experiment. Both Indium-113 and Indium-115 get converted into radioactive isotopes due to neutron irradiation. The neutron-induced reactions and the decay modes of the product isotopes are given below.

Indium-113 Activities

(1) $In^{113} + n^1 \longrightarrow In^{113m} + n^1$; $In^{113m} \xrightarrow{104m} In^{113}$ (stable)

(2) $In^{113} + n^1 \longrightarrow In^{114} \xrightarrow{72s} Sn^{114}$ (stable)

(3) $In^{113} + n^1 \longrightarrow In^{114m} \xrightarrow{49d} In^{114} \xrightarrow{72s} Sn^{114}$ (stable)

Indium-115 Activities

(4) $In^{115} + n^1 \rightarrow In^{115m} + n^1$; $In^{115m} \xrightarrow{4.5h} In^{115}$ (stable)

(5) $In^{115} + n^1 \rightarrow In^{116} \xrightarrow{13s} Sn^{116}$ (stable)

(6) $In^{115} + n^1 \rightarrow In^{116m} \xrightarrow{54m} Sn^{116}$ (stable)

Since in a foil activation experiment on neutron age to Indium-resonance the foils are counted after waiting for a measured period of about 10 minutes, the activities (2) and (5) are almost fully eliminated due to their very short half-lives. Also the activity (2) is very small because of the small percentage of Indium-113 in the activation foil. Thus no correction is applied to the measured activity in order to eliminate these two activities. The activities (1), (3) and (4) are mainly due to high energy neutrons for which the activation cross-sections are very small compared to the activation cross-section for the 54-minute main activity (6) which is mainly due to resonance neutrons. The activities (1) and (3) are very small because of the small percentage of In-113 in the activation foil. Since the foils are irradiated for about 9 hours (10 half-lives of the 54-minute-activity), the 49-day-activity builds up only to a very small fraction of its saturation value. Therefore, no correction is applied to the measured activity in order to eliminate these high energy activities (of course a correction is applied to the measured activity for eliminating that part of the 54-minute main activity (6) which is due high energy neutrons, in order to get the activity induced only by the neutrons of resonance energy) and it is

assumed that almost all the counts obtained from an Indium-foil, 10 minutes after it is taken out of the moderating medium, is due to the 54-minute activity of In^{116m} decaying into Sn^{116}. Thus the value of the decay constant λ in the equation (36) for calculating the saturation activity from the counts obtained, is calculated from this half-life.

CHAPTER III

EXPERIMENTAL SET-UP AND PROCEDURE

3.1 Description of the Set-up :

In a neutron age determination experiment using foil activation technique the main equipments needed are a tank for containing the moderating medium, the moderating material, an arrangement for holding the neutron source in position, an arrangement for suspending the foils and a beta-counting set-up. The detailed description of every equipment and the reason of its selection is given below.

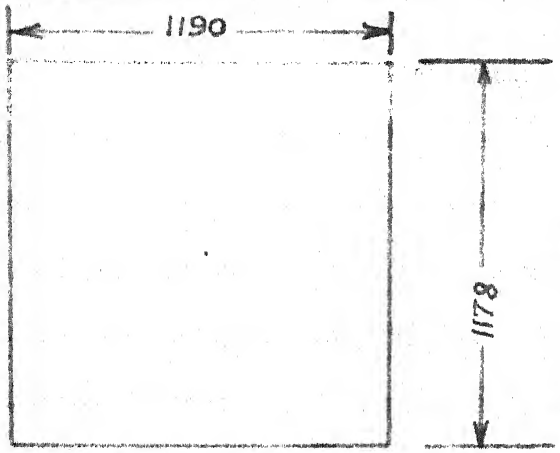
The Aluminium Tank

The moderating medium in which the neutron age was determined, that is, the Aluminium-water slab lattice, was contained in an aluminium tank of inside dimensions 120.5 cms x 120.5 cms x 120.5 cms, made of 6.35 mms thick plates. Aluminium was used mainly to overcome the troubles due to corrosion and the radioactivity that the tank might acquire due to long exposure to neutrons during the experiment. The contamination by dust, etc. of the moderating medium in the tank was prevented by covering the tank with a pair of 122 cms x 91.5 cms x 6.35 mms thick perspex sheets. One of the sheets overlapped the other in the middle portion of the top of the tank, and the sheets could easily be separated from each other by sliding them apart thus getting a straight opening in the middle sufficient for taking out the foils. In order to close the small slits left by the perspex sheets the tank was further covered by a polythene jacket.

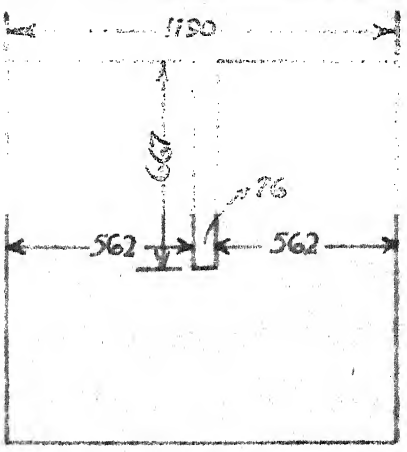
The Aluminium Plates

The tank contained a series of ninety 119.0 cms wide x 117.8 cms high x 3.175 mms thick plates (shown in Figure 1) of commercial Aluminium (99.76% pure by weight), all held parallel to one another at a gap of one centimetre in-between, with the help of a pair of spacers (shown in Figure 1) at the bottom and a pair of spacers at the top. The spacers were made of 2.54 cms x 2.54 cms x 3.175 mms thick aluminium angle by cutting one of the arms of the angle at a regular spacing of one centimetre. The number of cuts in a spacer was equal to the number of the aluminium plates, and the cuts were made so wide that the plates were push-fit into the spacers. The central six aluminium plates each (shown in Figure 1) had a vertical rectangular cut from the top about the vertical centre line. The cuts, 66.7 cms deep x 7.6 cms wide, in the plates were designed to form a central cavity for accommodating the neutron source container at a central location inside the moderating medium. In order to have the desired Aluminium-water slab lattice above the neutron source container, a sliding piece of 3.175 mms thick aluminium plate (shown in Figure 1) was fitted into the cut of everyone of the six central plates. The sliding pieces were just as wide as the cuts in the central aluminium plates and could fully close the portion of the cuts above the neutron source container. Finally, four rows, two at the top and two at the bottom, of one centimetre long pieces of aluminium tube were pushed into the gaps between the aluminium plates, in order to keep the plates parallel to one another all through at the desired spacing of one centimetre.

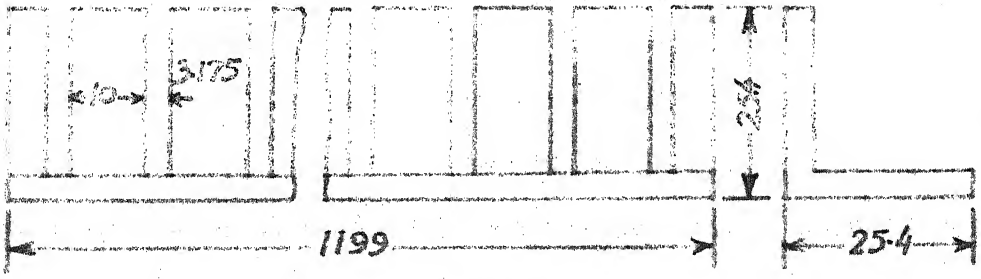
FIGURE 1



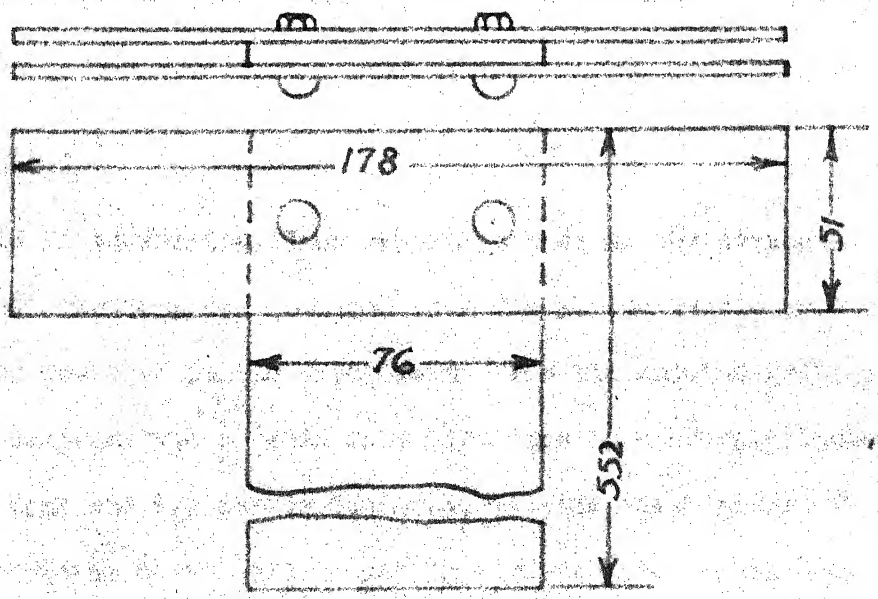
Al-Plate, 84 Thus



Cut Plate, 6 Thus



Spacer, 4 Thus



Sliding Piece, 6 Thus

Pure Light Water

In order to get the desired Aluminium-water slab lattice, more than 1000 litres of pure light water was required to fill in the spaces between the aluminium plates. Tap water had a conductivity of about 1000 micromhos/cm and so it required a considerable amount of purification[14]. Tap water after distillation had a conductivity of about 20 micromhos/cm[14] whereas the conductivity of the tap water was measured to be only about 0.2 micromhos/cm after passing it through a four-column I.A.E.C. demineraliser plant. Hence the demineralised tap water of conductivity 0.2 micromhos/cm was used in the experiment. This water contained a total of only about 1.6 parts per million of dissolved solids. The demineraliser plant consisted of an active carbon fitter, a cation exchange column, an anion exchange column and a mixed bed column, and required a regeneration of the cation and the anion exchange columns after giving an output of about 1000 litres of pure water. In order to continuously check the purity of the demineralised water, the output of the demineraliser was passed through a conductivitymeter before it entered into the tank.

The Neutron Source

A 5-curie Plutonium-Beryllium neutron source of the strength of about 8×10^6 neutrons/sec obtained from the Bhabha Atomic Research Centre, Trombay was used in the experiment. The Plutonium-Beryllium intermetallic compound was covered from all sides in a steel cylindrical cover 7.3 cms high and 5.3 cms in diameter. As the steel cover had no holding part attached to it, it was put in a rectangular source container (shown in Figure 3) made of Perspex, which was suspended by a steel wire.

Plutonium-Beryllium neutron source is an energy-distributed source having a characteristic energy-spectrum[15] (shown in Figure 2) ranging from roughly zero to about 10.6 MeV with an average neutron energy of about 4.2 MeV[16]. Since the half-life of Plutonium is 24,300 years it is very reasonable to assume the source to remain steady during a few days of an experiment for neutron age determination.

The Activation Foils

The activation foils used in the experiment were made of pure Indium containing 95.77% of Indium-115 and 4.23% of Indium-113, and were 12.7 mms in diameter and 0.254 mm thick. In order to eliminate activities due to thermal neutrons the foils were put in Cadmium-cover sets which absorbed almost all the incoming thermal neutrons. In order to suspend the foils at desired locations inside the moderating medium, the Cadmium-covered Indium foils were put into foil holders (shown in Figure 3) which were suspended from a foil suspension rod (shown in Figure 3) by nylon thread. The foil suspension rod was a straight aluminium rod 130 cms long having fine diametrical holes at a distance of 13.175 mms in-between. The rod could be simply supported, both in the parallel and perpendicular directions, with its ends resting in grooves cut at the top of the sides of the tank. The rod could slide in the grooves a few centimetres along its length and be fixed in a desired position with the help of a pair of sliding aluminium rings having side screws, at the ends of the rod.

The foil holders were made of Perspex in order to minimise the flux perturbation caused by introducing another material in the moderating

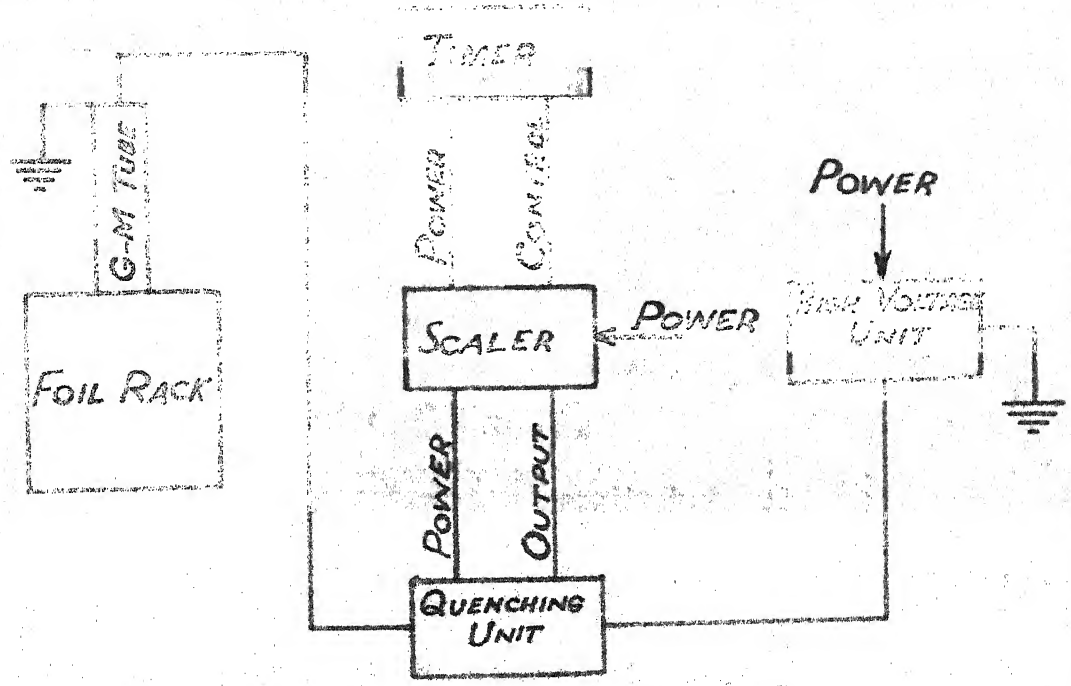
medium. This flux perturbation is minimum if the difference between the moderating ratios of the material introduced and the moderating medium displaced, is minimum. The moderating ratio of Perspex is 153.6 and that of light water (the moderating medium displaced) is 147.0, and hence the flux perturbation was negligible.

The foil suspension rod was fixed in the position in which the central diametrical hole in the rod was vertically above the middle point of the gap between the central pair of aluminium plates, and the neutron source container was lowered down into the central cavity, with the help of the steel wire attached to the container and passing through the central diametrical hole in the rod. The foil holders were suspended into the gaps between the aluminium plates through the other holes in the rod (the holes were vertically above the middle points of the gaps). The foil holders were kept in position by small Lead-weights suspended from the bottom of the foil holders by nylon thread about 36.8 cms long. The centres of the neutron source and the activation foils were all in a horizontal plane exactly 63.8 cms below the axis of the foil suspension rod. The figure 5 is a plan of the set-up showing the positions of the neutron source and the foils.

The Beta-Counting Set-up

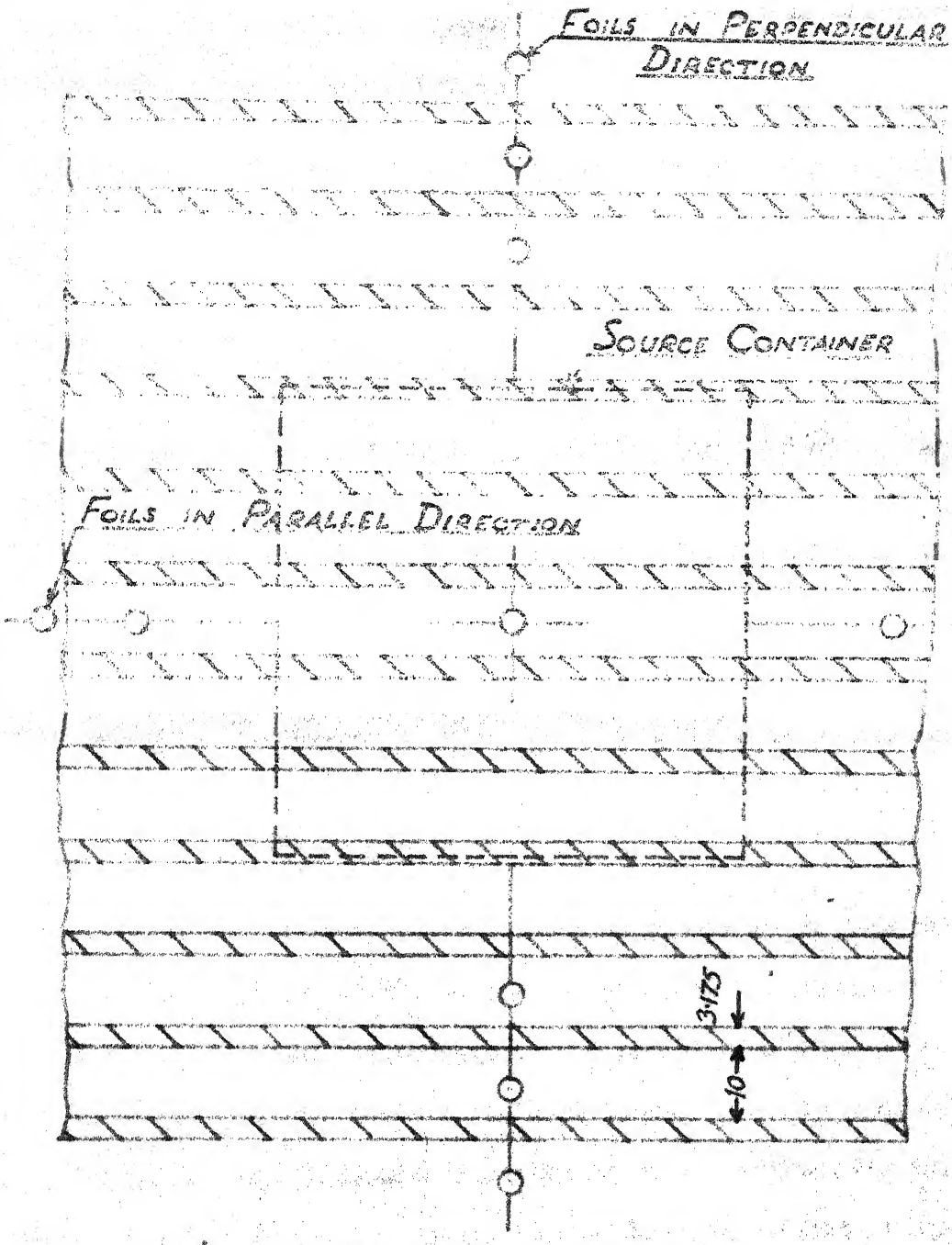
The Geiger-Mueller counting set-up whose schematic diagram is shown in the Figure 4, was used in the experiment. The pulses from the G-M tube were first passed the quenching unit. The undesirable pulses due to the electrons liberated from the cathode of the tube by the

FIGURE 4



GM COUNTING SET-UP

FIGURE 5



PLAN IN PART

interaction of the positive ions and the unavoidable gamma rays produced in the tube during counting were quenched in this unit. The output pulses from the quenching unit were counted by the decade scaler. The counting time was set at 10 minutes with the help of the preset timer. The G-M tube with the foil rack was kept inside a Lead-castle in order to reduce the background count rate of the counting system. The flattest portion of the curve of the count rate, obtained due to an intense beta-source kept on the shelf no. 2 of the foil rack (the shelf no.2 was used throughout the experiment), against the high voltage applied to the G-M tube, had a slope of about 4% of the count rate per 100-Volt of the high voltage, and this plateau was obtained at a high voltage of 1500 $\pm$ 100 Volts, and hence the tube was operated at a high voltage of 1500 Volts obtained from a highly stabilised high voltage unit which was connected to the 220 Volts-mains through a voltage stabiliser.

3.2 Procedure of the Experiment :

The foils were tied to the foil suspension rod at an interval of 2.635 cms starting at a distance of 5.27 cms from the centre of the neutron source, and first, measurements were made in the perpendicular direction. At a time only three foils were lowered into the moderating medium in order to keep a minimum distance of 15 cms between any pair of foils, which is required to eliminate the shadowing effect of one foil on another. The time of putting the foils in the moderating medium was roughly noted. After about 9 hours of irradiation (when the foils acquired more than 99.9% of their saturation activities) the foils were

taken out of the medium one by one and counted. The instant at which a foil was taken out was roughly noted, and a stop-watch was started exactly at that instant. Ten minutes after the foil was taken out, the total number of counts from the first side of the foil in a counting time of 10 minutes was obtained with the G-M counting set-up. In a minute the side of the foil was changed and the second side was counted. In this way, both the Cadmium-covered Indium foils, and the Cadmium- and Indium-covered Indium foils at all the positions in the perpendicular direction were counted. Care was taken not to use a foil within about 9 hours after it was taken out of the moderating medium, in order that its activity might drop down to a negligible value (less than 0.1% of the saturation activity). The background was counted for 10 minutes (a period equal to the counting time of the foil) just before counting the first side and just after counting the second side of every foil. The experimental data for the perpendicular case are given in Tables (7) and (8). After this the foil suspension rod was put parallel to the aluminium plates, and the foils were suspended into the same (central) gap. The same sets of readings were taken and the experimental data for the parallel case are given in Tables (2) and (3).

CHAPTER IV

CALCULATION, RESULTS AND DISCUSSION

4.1 Corrections to the Saturation Activities :

Using the equation (36) the saturation activities at various distances from the neutron source are calculated. While counting an activated foil, the background counts add to the actual number of counts of the foil and hence a correction is applied to the total number of counts observed from the activated foil in order to correct for this. Since Indium has a finite activation cross-section for neutrons of energies higher than the resonance energy, a fraction of the saturation activity of a Cadmium-covered Indium foil, though small, is induced by the high energy neutrons. Hence a correction is applied to the Cadmium-covered Indium foil activities in order to eliminate the high energy activity. In a foil activation experiment for neutron age measurement, the neutron source and the activation foil are both necessarily of finite sizes, but the saturation activities required for the calculation of the neutron age are those arising from a point neutron source at specified points in the moderating medium. Hence a correction is applied to the measured saturation activities in order to obtain the correct activities arising from a point source at specified points. All these corrections are explained below.

Background Correction

In order to correct for background, the number of background counts

observed for a period of time equal to the counting time of the foil, just before the first side of the foil is counted, is subtracted from the total number of counts obtained from the first side. In order to correct the total number of counts obtained from the second side of the foil, the number of background counts observed for a period of time equal to the counting time of the foil, just after the second side of the foil is counted, is subtracted from it.

Correction for High-Energy Activation[17]

In order to correct for high-energy activation, a single Cadmium-covered Indium foil and a Cadmium-covered sandwich of three similar Indium foils are activated one after the other at the same point in the moderating medium. The saturation activity of a single Cadmium-covered Indium foil is due to neutrons of both the resonance energy and the higher energies. The neutrons of the thermal region are absorbed by the Cadmium-cover itself. The saturation activity of the interior Indium foil of the sandwich is due only to the high-energy neutrons since the resonance neutrons are absorbed by the outer Indium foils of the sandwich. Therefore, the saturation activity of the interior Indium foil of the sandwich is subtracted from the activity of the single Cadmium-covered Indium foil, and the result is the saturation activity induced only the neutrons of the resonance energy. Thus the equation for correcting for the high-energy activation is

$$A_s(\text{resonance}) = A_s(\text{Cd-covered}) - A_s(\text{Cd+In-covered}) \qquad (37)$$

Correction for Finite Sizes of Source and Foil

The measured saturation activities, that is, the saturation activities corrected for background and high-energy activation, are corrected for the finite sizes of the neutron source and the activation foil by the approximate formula[18]

$$A(r) = A_m(r) - \frac{k}{r}\frac{dA}{dr}, \tag{38}$$

where $k = \frac{X^2 + Y^2 + 6a^2}{24}$ (39)

$A(r)$ = the saturation activity corrected for the finite sizes of the source and the foil,

$A_m(r)$ = the measured saturation activity,

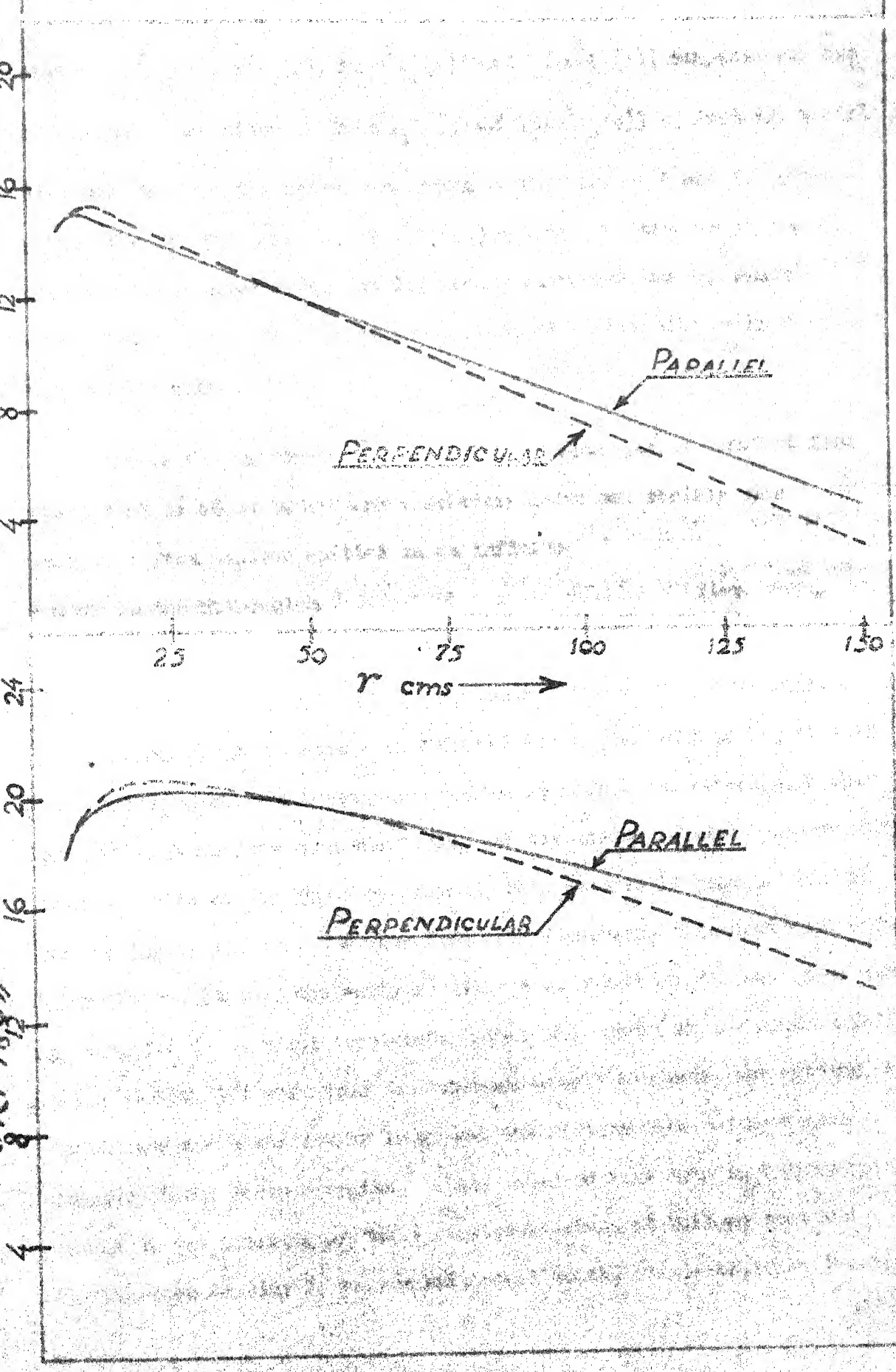
X, Y = the length and the diameter of the source,

and a = the radius of the activation foil.

This formula assumes a uniform distribution of the total strength of the neutron source over the projected area of the source on a plane passing through its centre and parallel to the face of the activation foil.

4.2 Calculation and Results :

Using the saturation activities corrected for the finite sizes of the source and the foil, by the equations (38) and (39), the 2nd and the 4th moments of the activities and their natural logarithms,


20
16
12
8
4
PARALLEL
PERPENDICULAR
25
50
75
100
125
150
r cms
24
20
16
12
8
4
PARALLEL
PERPENDICULAR

that is, $r^2A_s(r)$, $r^4A_s(r)$, $\ln(r^2A_s(r))$ and $\ln(r^4A_s(r))$ respectively are calculated. The plots of $\ln(r^2A_s(r))$ and $\ln(r^4A_s(r))$ against the radial distance r from the source are shown in the Figures 6 and 7. The point at which the curve of $\ln(r^2A_s(r))$ against r becomes straight is noted. The areas under the 2nd moment curve and the 4th moment curve from r = o to this point are calculated numerically using the trapezoidal rule.

Since the scattering cross-section of Hydrogen is constant from about 1 eV to about 10 keV and thereafter decreases rapidly with increasing energy, a fast neutron emitted in an infinite hydrogenous medium with its energy in the MeV-region undergoes its first collision after travelling a large distance from the point where it is emitted (the scattering mean free path is large). Since the neutron loses, on the average, a large fraction of its energy in this collision (the average logarithmic energy decrement in a hydrogenous medium is high), the second mean free path is much shorter than the first, and the second collision occurs very near the site of the first collision. This process is repeated at all succeeding collisions, the mean free path decreasing with each collision, with the result that the neutron travels only a short distance from the point where it is first scattered. After the energy of the neutron falls below 10 keV, the mean free path remains nearly constant, but now the scattering cross-section is large and the neutron does not move much farther at the lower energies. Since neutrons slow down in a hydrogenous medium in the vicinity of their first collision, it follows that the slowing-down density is very nearly equal to the first-collision density

which is given by the product of the uncollided flux and the macroscopic scattering cross-section at the source energy. For a point isotropic steady monoenergetic source emitting S neutrons/sec at the energy E_o in an infinite medium, q(r) is therefore given by the equation

$$q(r) = \frac{S \sum_{sm}(E_o) e^{-\sum_{sm}(E_o) r}}{4 \pi r^2} \qquad (40)$$

The equation (40) fairly well represents the slowing-down density only at large distances from the neutron source because only those neutrons which have their first collision at large distances from the source (some source-neutrons do have their first collision at small distances from the source) move before their first collision as far from the source as they are ever going to go. A neutron which has its first collision very near the source and slows down to the eV-region in succeeding collisions near the source, contributes to the slowing-down densities at all points in the vicinity of the source, and hence the slowing-down density at small distances from the source is not just the first-collision density.

The areas under the 2nd moment curve and the 4th moment curve from the point where the curve of $\ln(r^2 A_g(r))$ against r becomes straight, to r = ∞ are calculated analytically using the above fact that the slowing-down density or the neutron flux and hence also the saturation activity, at large distances from the source, is fairly well represented by an equation of the form

$$A_g(r) = \frac{a e^{br}}{r^2} \quad (b \text{ is negative}) \qquad (41)$$

The equation (41) can be written as

$$\ln(r^2 A_s(r)) = \ln a + br \tag{42}$$

and hence the plot of $\ln(r^2 A_s(r))$ against r is a straight line.

The values of the constants a and b are determined by fitting a least-square straight line over the fairly straight portion of the plot of $\ln(r^2 A_s(r))$ against r. Using r_m for the distance at which the plot of $\ln(r^2 A_s(r))$ against r becomes straight, the following results of integration are used.

$$\int_{r_m}^{\infty} r^2 A_s(r)dr = -\frac{a}{b} e^{br_m} \tag{43}$$

$$\int_{r_m}^{\infty} r^4 A_s(r)dr = -\frac{a}{b^3} e^{br_m} (b^2 r_m^2 - 2br_m + 2) \tag{44}$$

Finally the total areas under the 2nd moment curve and the 4th moment curve are found by adding the numerical and the analytical parts, and the neutron age is calculated using the equation (24).

The final results of calculation in the parallel and perpendicular directions are shown in Tables (6) and (11) respectively. Also the respective intermediate results of calculation are shown in the Tables (4) and (5), and (9) and (10).

4.3 Analysis of the Statistical Error[19]

Due to the fact that the basic process of radioactive disintegration is statistical in nature, the number of counts observed in a certain period of time from an activated foil is not exact but carries an error called statistical error. The statistical error in an observed number of counts N is $\pm \sqrt{N}$. The following basic rules for error estimation are used. If two quantities R_1 and R_2 carry the statistical errors $\pm r_1$ and $\pm r_2$ respectively, then

$$\text{Error in } (R_1 \pm R_2) = \pm \sqrt{r_1^2 + r_2^2}, \tag{45}$$

$$\text{Error in } R_1R_2 = \pm R_1R_2 \sqrt{\frac{r_1^2}{R_1^2} + \frac{r_2^2}{R_2^2}}, \text{ and} \tag{46}$$

$$\text{Error in } \frac{R_1}{R_2} = \pm \frac{R_1}{R_2} \sqrt{\frac{r_1^2}{R_1^2} + \frac{r_2^2}{R_2^2}} \tag{47}$$

Starting from the statistical errors in the observed number of counts, the statistical errors in all the quantities calculated at intermediate steps in the calculation of the neutron age, are estimated using the basic rules (45)-(47). Finally the statistical errors in the total areas under the 2nd moment curve and the 4th moment curve are found. The analytical parts of these areas are assumed to carry no statistical error since the constants a and b are determined by a least-square fit over a fairly large number of points and carry comparatively neglible

statistical error. The statistical error in the age value is then calculated using the rule (47). The errors in the age values in the parallel and perpendicular directions are shown in the Tables (6) and (11) with the values themselves.

4.4 Discussion of the Results :

Using all necessary corrections the neutron ages in the parallel and perpendicular directions are found to be 79.33 ± 0.444 cm^2 and 71.85 ± 0.470 cm^2 respectively. Though both experimental and theoretical age values of fission neutrons to Indium resonance, parallel and perpendicular to plates in Aluminium-water slab lattices, are available in the literature, values for the age of Pu-Be neutrons to Indium resonance in the parallel and perpendicular directions are not available up to 1969. The neutron age in the parallel direction is greater than that in the perpendicular direction. This is so in the case of available values for fission neutrons also.[11,12] This is due probably to the following reason.

Using the symbols x and y for the volume-fractions of Aluminium and water respectively in the lattice, a neutron slowing down in the perpendicular direction has a fraction x of its path through Aluminium and the fraction y through water. Also an average neutron slowing down in the parallel direction has a fraction x of its path through Aluminium and the fraction y through water since out of all paths in the parallel direction, some (whose number is proportional to the fraction x) are all the way through Aluminium and some (whose

number is proportional to the fraction y) are all the way through water. So, volumetrically speaking, a neutron on the average has the same fraction of its path through Aluminium in both the directions. Since the neutron age in pure Aluminium is much greater than that in pure water, the age-average macroscopic scattering cross-section (which is assumed here to be the basis of qualitative reasonings in matters of age) of Aluminium is smaller than that of water. Due to this a neutron slowing down in the parallel direction has a comparatively smaller probability to be scattered out of Aluminium if it is in Aluminium and a larger probability to be scattered out of water if it is in water. The fractions of the path of a neutron slowing down in the perpendicular direction remain unaffected by this difference in scattering cross-section but an average neutron in the parallel direction has a fraction greater than x of its path through Aluminium, and hence the age in the parallel direction is greater than that in the perpendicular direction.

Finally these values of neutron age are actually flux ages and not slowing-down density ages in their respective directions. This is due to the fact that the saturation activity is proportional to the neutron flux (the equation (17)), and only if the Age Theory is assumed it is proportional to the slowing-down density also (the equation (21)). Since the moderating medium is heterogeneous, the slowing-down density is discontinuous at all Aluminium-water interfaces. Using the equation (21) with activation measurements made in water, slowing-down densities at certain points in water only are known. From these measured values of slowing-down density in water-layers, the values of slowing-down density

in Aluminium-plates can only roughly be estimated by matching the neutron fluxes in Aluminium and water at each interface, using scattering cross-sections of Aluminium and water averaged in a suitable way over Indium resonance energy region. Hence simply the flux moments have been used in calculating the neutron ages.

APPENDIX

AGE-AVERAGE SCATTERING CROSS-SECTION

According to the Fermi Age Theory the neutron age from an energy E_o to a lower energy E in a homogenous moderating medium is given by the equation[20]

$$\tau(E_o \rightarrow E) = \int_E^{E_o} \frac{D(E)dE}{\xi \Sigma_{sm}(E)} \tag{48}$$

where $D(E)$ = the energy-dependent diffusion coefficient of the moderator and is in turn related to the scattering cross-section by the equation[21]

$$D(E) = \frac{1}{3 \Sigma_{sm}(E)(1-\bar{\mu})} \tag{49}$$

where $\bar{\mu}$ = the average value of the cosine of the scattering angle in the laboratory system.

Using the equation (49) the neutron age is expressed in terms of scattering cross-section only and thus

$$\tau(E_o \rightarrow E) = \frac{1}{3\xi(1-\bar{\mu})} \int_E^{E_o} \frac{dE}{\Sigma_{sm}^2(E)} \tag{50}$$

Now the Fermi age-average scattering cross-section of a homogenous moderator over a specified energy interval is defined as that constant

scattering cross-section which if used in the equation (50) gives the correct (that is, the experimentally measured) value of neutron age in the moderator over the specified interval.

Using the symbol $(\Sigma_{sm})_\tau$ for the age-average value, the neutron age from E_o to E is written as

$$\tau(E_o \rightarrow E) = \frac{1}{3\xi(1-\bar{\mu})(\Sigma_{sm})_\tau^2} \int_E^{E_o} \frac{dE}{E} \qquad (51)$$

Combining the equations (50) and (51) the age-average scattering cross-section is written as

$$(\Sigma_{sm})_\tau = \sqrt{\int_E^{E_o} \frac{dE}{E} \Big/ \int_E^{E_o} \frac{dE}{E\Sigma_{sm}^2(E)}} \qquad (52)$$

The age-average scattering cross-section is defined only for a homogenous moderating medium and is different for different energy intervals for the same moderator.

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COUNTS OF CADMIUM-COVERED INDIUM FOILS IN PARALLEL DIRECTION

ISTANCE CMS	BACKGROUND BEFORE	AFTER	WAITING TIME BEFORE 1ST SIDE	2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	2ND SIDE
5.27	0.8760E 03	0.2489E 04	10.0	21.0	10.0	0.9272E 04	0.8747E 04
7.90	0.1580E 03	0.1030E 03	10.0	21.0	10.0	0.4339E 04	0.4573E 04
10.54	0.3750E 03	0.3750E 03	10.0	22.0	10.0	0.3056E 04	0.3740E 04
13.17	0.1750E 03	0.1750E 03	10.0	21.0	10.0	0.1152E 04	0.1587E 04
15.81	0.1030E 03	0.3650E 03	10.0	21.0	10.0	0.9470E 03	0.1050E 04
18.44	0.1150E 03	0.3220E 03	10.0	21.0	10.0	0.8600E 03	0.6970E 03
21.08	0.2100E 03	0.3580E 03	10.0	23.0	10.0	0.5740E 03	0.5490E 03
23.71	0.1490E 03	0.1740E 03	10.0	23.0	10.0	0.3480E 03	0.3640E 03
26.35	0.8600E 02	0.1750E 03	10.0	22.0	10.0	0.1500E 03	0.2360E 03
28.98	0.5900E 02	0.8700E 02	10.0	21.0	10.0	0.1170E 03	0.1670E 03

TABLE 3

COUNTS OF CADMIUM- AND INDIUM-COVERED INDIUM FOILS IN PARALLEL DIRECTION

ISTANCE CMS	BACKGROUND BEFORE	AFTER	WAITING TIME BEFORE 1ST SIDE	2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	2ND SIDE
5.27	0.1320E 03	0.8040E 03	10.0	21.0	10.0	0.3976E 04	0.4410E 04
7.90	0.3020E 03	0.9910E 03	10.0	24.0	10.0	0.3304E 04	0.3306E 04
10.54	0.1330E 03	0.2190E 03	10.0	21.0	10.0	0.1381E 04	0.1387E 04
13.17	0.1170E 03	0.1480E 03	11.0	21.0	10.0	0.7450E 03	0.6980E 03
15.81	0.1330E 03	0.1230E 03	10.0	21.0	10.0	0.5030E 03	0.5110E 03
18.44	0.1690E 03	0.2880E 02	10.0	21.0	10.0	0.4940E 02	0.5960E 02
21.08	0.1560E 03	0.1940E 03	10.0	21.0	10.0	0.2800E 03	0.3260E 03
23.71	0.1390E 03	0.1690E 03	10.0	21.0	10.0	0.2510E 03	0.2620E 03
26.35	0.1790E 03	0.1000E 03	10.0	21.0	10.0	0.1480E 03	0.1280E 03
28.98	0.1180E 03	0.1110E 03	10.0	21.0	10.0	0.1610E 03	0.1240E 03

TABLE 4

TABLE OF CORRECTED ACTIVITIES IN PARALLEL DIRECTION

ISTANCE CMS	CADMIUM-COVERED ACTIVITY	(CD+IN)-COVERED ACTIVITY	RESONANCE ACTIVITY	ACTIVITY CORRECTED FOR FINITE SOURCE AND FOIL
5.27	0.1475E 06	0.7549E 05	0.7203E 05	0.7741E 05
7.90	0.1074E 06	0.5449E 05	0.5292E 05	0.5601E 05
10.54	0.6236E 05	0.2448E 05	0.3788E 05	0.4051E 05
13.17	0.2457E 05	0.1198E 05	0.1259E 05	0.1422E 05
15.81	0.1541E 05	0.7711E 04	0.7703E 04	0.8095E 04
18.44	0.1111E 05	0.6416E 04	0.4693E 04	0.4874E 04
21.08	0.5566E 04	0.2606E 04	0.2961E 04	0.3052E 04
23.71	0.3998E 04	0.2068E 04	0.1929E 04	0.1978E 04
26.35	0.1298E 04	0.1176E 02	0.1286E 04	0.1315E 04
28.98	0.1417E 04	0.5472E 03	0.8700E 03	0.8893E 03

TABLE 5

TABLE OF MOMENTS OF CORRECTED ACTIVITIES IN PARALLEL DIRECTION

ISTANCE CMS	CORRECTED ACTIVITY	2ND MOMENT	4TH MOMENT	LOG(2ND MOMENT)	LOG(4TH MOMENT)
5.27	0.7741E 05	0.2150E 07	0.5971E 08	0.1458E 02	0.1740E 02
7.90	0.5601E 05	0.3500E 07	0.2187E 09	0.1507E 02	0.1926E 02
10.54	0.4051E 05	0.4500E 07	0.5000E 09	0.1532E 02	0.2009E 02
13.17	0.1422E 05	0.2468E 07	0.4284E 09	0.1472E 02	0.1988E 02
15.81	0.8095E 04	0.2023E 07	0.5057E 09	0.1452E 02	0.2004E 02
18.44	0.4874E 04	0.1658E 07	0.5642E 09	0.1432E 02	0.2015E 02
21.08	0.3052E 04	0.1356E 07	0.6026E 09	0.1412E 02	0.2022E 02
23.71	0.1978E 04	0.1112E 07	0.6256E 09	0.1392E 02	0.2025E 02
26.35	0.1313E 04	0.9120E 06	0.6332E 09	0.1372E 02	0.2027E 02
28.98	0.8893E 03	0.7472E 06	0.6277E 09	0.1352E 02	0.2026E 02

FINAL RESULTS IN THE PARALLEL DIRECTION

THICKNESS OF ALUMINUM PLATE=0.3175 CMS
THICKNESS OF WATER LAYER IN-BETWEEN=1.0000 CMS

LEAST SQUARE CONSTANT A= 0.6683E 07
LEAST SQUARE CONSTANT B= -0.7560E-01

EXPONENTIAL PART OF AREA UNDER SECOND MOMENT CURVE= 0.3765E 08
NON-EXPONENTIAL PART OF AREA UNDER SECOND MOMENT CURVE= 0.3283E 08
TOTAL AREA UNDER SECOND MOMENT CURVE= 0.6548E 08+- 0.3568E 06

EXPONENTIAL PART OF AREA UNDER FOURTH MOMENT CURVE= 0.2847E 11
NON-EXPONENTIAL PART OF AREA UNDER FOURTH MOMENT CURVE= 0.2694E 10
TOTAL AREA UNDER FOURTH MOMENT CURVE= 0.3117E 11+- 0.3916E 08

AGE IN PARALLEL DIRECTION= 79.33+- 0.4436E 00

COUNTS OF CADMIUM-COVERED INDIUM FOILS IN PERPENDICULAR DIRECTION

DISTANCE CMS	BACKGROUND BEFORE	BACKGROUND AFTER	WAITING TIME BEFORE 1ST SIDE	WAITING TIME BEFORE 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE
5.27	0.8800E 02	0.8800E 02	10.0	21.0	10.0	0.7050E 04	0.6257E 04
7.90	0.9000E 02	0.1000E 03	10.0	21.0	10.0	0.4410E 04	0.5493E 04
10.54	0.9800E 02	0.1590E 03	10.0	21.0	10.0	0.2730E 04	0.3313E 04
13.17	0.5320E 03	0.5320E 03	10.0	21.0	10.0	0.2181E 04	0.2212E 04
15.81	0.5320E 03	0.5320E 03	10.0	21.0	10.0	0.1590E 04	0.1380E 04
18.44	0.9800E 02	0.1590E 03	10.0	21.0	10.0	0.8270E 03	0.7170E 03
21.08	0.8800E 02	0.8800E 02	10.0	21.0	10.0	0.3360E 03	0.4600E 03
23.71	0.9000E 02	0.9000E 02	10.0	21.0	10.0	0.1670E 03	0.3310E 03
26.35	0.9800E 02	0.1590E 03	10.0	21.0	10.0	0.3040E 03	0.2860E 03
28.98	0.1280E 03	0.1280E 03	10.0	21.0	10.0	0.1640E 03	0.2570E 03
31.62	0.1500E 03	0.2030E 03	10.0	21.0	10.0	0.1720E 03	0.3010E 03
34.25	0.9800E 02	0.1010E 03	10.0	21.0	10.0	0.1420E 03	0.1690E 03
36.89	0.1090E 03	0.1190E 03	10.0	21.0	10.0	0.1290E 03	0.1430E 03

COUNTS OF CADMIUM- AND INDIUM-COVERED INDIUM FOILS IN PERPENDICULAR DIRECTION

DISTANCE CMS	BACKGROUND BEFORE	BACKGROUND AFTER	WAITING TIME BEFORE 1ST SIDE	WAITING TIME BEFORE 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE
5.27	0.1190E 03	0.2790E 03	10.0	21.0	10.0	0.2846E 04	0.2693E 04
7.90	0.7700E 02	0.8800E 02	10.0	21.0	10.0	0.2358E 04	0.2197E 04
10.54	0.1030E 03	0.1510E 03	10.0	21.0	10.0	0.1058E 04	0.1032E 04
13.17	0.8800E 02	0.8200E 02	10.0	21.0	10.0	0.8630E 03	0.9130E 03
15.81	0.3330E 03	0.5650E 03	10.0	21.0	10.0	0.8020E 03	0.8[illegible]E 03
18.44	0.2000E 03	0.2130E 03	10.0	21.0	10.0	0.5120E 03	0.4[illegible]E 03
21.08	0.1060E 03	0.1030E 03	10.0	21.0	10.0	0.2430E 03	0.1[illegible]E 03
23.71	0.8200E 02	0.1060E 03	10.0	21.0	10.0	0.2090E 03	0.1[illegible]E 03
26.35	0.1200E 03	0.1290E 03	10.0	21.0	10.0	0.2080E 03	0.2[illegible]E 03
28.98	0.1570E 03	0.3060E 03	8.0	19.0	10.0	0.2170E 03	0.3[illegible]E 03
31.62	0.1130E 03	0.1570E 03	10.0	22.0	10.0	0.1560E 03	0.1[illegible]E 03
34.25	0.1480E 03	0.2100E 03	10.0	21.0	10.0	0.1840E 03	0.2[illegible]E 03
36.89	0.1480E 03	0.1510E 03	10.0	21.0	10.0	0.1530E 03	0.1[illegible]E 03

TABLE OF CORRECTED ACTIVITIES IN PERPENDICULAR DIRECTION

DISTANCE CMS	CADMIUM-COVERED ACTIVITY	(CD+IN)-COVERED ACTIVITY	RESONANCE ACTIVITY	ACTIVITY CORRECTED FOR FINITE SOURCE AND FOIL
5.27	0.1328E 06	0.5199E 05	0.8060E 05	0.8821E 05
7.90	0.9941E 05	0.4446E 05	0.5495E 05	0.5873E 05
10.54	0.5913E 05	0.1859E 05	0.4054E 05	0.4304E 05
13.17	0.3383E 05	0.1635E 05	0.1748E 05	0.1901E 05
15.81	0.1921E 05	0.7167E 04	0.1204E 05	0.1253E 05
18.44	0.1295E 05	0.5978E 04	0.6969E 04	0.7262E 04
21.08	0.6385E 04	0.2141E 04	0.4244E 04	0.4386E 04
23.71	0.4434E 04	0.1775E 04	0.2659E 04	0.2732E 04
26.35	0.3325E 04	0.1613E 04	0.1712E 04	0.1752E 04
28.98	0.1688E 04	0.5732E 03	0.1115E 04	0.1137E 04
31.62	0.1284E 04	0.5381E 03	0.7459E 03	0.7591E 03
34.25	0.1155E 04	0.4551E 03	0.4995E 03	0.5075E 03
36.89	0.4497E 03	0.1124E 03	0.3373E 03	0.3432E 03

TABLE OF MOMENTS OF CORRECTED ACTIVITIES IN PERPENDICULAR DIRECTION

DISTANCE CMS	CORRECTED ACTIVITY	2ND MOMENT	4TH MOMENT	LOG(2ND MOMENT)	LOG(4TH MOMENT)
5.27	0.8821E 05	0.2450E 07	0.6604E 08	0.1471E 02	0.1804E 02
7.90	0.5873E 05	0.3670E 07	0.2294E 09	0.1512E 02	0.1925E 02
10.54	0.4304E 05	0.4781E 07	0.5311E 09	0.1538E 02	0.2009E 02
13.17	0.1901E 05	0.3300E 07	0.5729E 09	0.1501E 02	0.2017E 02
15.81	0.1253E 05	0.3132E 07	0.7830E 09	0.1496E 02	0.2048E 02
18.44	0.7262E 04	0.2471E 07	0.8406E 09	0.1472E 02	0.2055E 02
21.08	0.4386E 04	0.1949E 07	0.8661E 09	0.1448E 02	0.2058E 02
23.71	0.2732E 04	0.1537E 07	0.8643E 09	0.1425E 02	0.2058E 02
26.35	0.1752E 04	0.1216E 07	0.8446E 09	0.1401E 02	0.2055E 02
28.98	0.1137E 04	0.9555E 06	0.8027E 09	0.1377E 02	0.2050E 02
31.62	0.7591E 03	0.7589E 06	0.7588E 09	0.1354E 02	0.2045E 02
34.25	0.5075E 03	0.5955E 06	0.6988E 09	0.1330E 02	0.2036E 02
36.89	0.3432E 03	0.4670E 06	0.6356E 09	0.1305E 02	0.2027E 02

FINAL RESULTS IN THE PERPENDICULAR DIRECTION

THICKNESS OF ALUMINUM PLATE=0.3175 CMS
THICKNESS OF WATER LAYER IN-BETWEEN=1.0000 CMS

LEAST SQUARE CONSTANT A= 0.1303E 08
LEAST SQUARE CONSTANT B= -0.9009E-01

EXPONENTIAL PART OF AREA UNDER SECOND MOMENT CURVE= 0.3480E 08
NON-EXPONENTIAL PART OF AREA UNDER SECOND MOMENT CURVE= 0.4478E 08
TOTAL AREA UNDER SECOND MOMENT CURVE= 0.7958E 08+- 0.4801E 06

EXPONENTIAL PART OF AREA UNDER FOURTH MOMENT CURVE= 0.2949E 11
NON-EXPONENTIAL PART OF AREA UNDER FOURTH MOMENT CURVE= 0.4814E 10
TOTAL AREA UNDER FOURTH MOMENT CURVE= 0.3430E 11+- 0.8737E 05

AGE IN PERPENDICULAR DIRECTION= 71.85+- 0.4705E 00
